Welding of Stainless steel

1.0 INTRODUCTION:

Stainless steels or, more precisely, corrosion-resisting steels are a family of iron-base alloys having excellent resistance to corrosion. The term “stainless” implies a resistance to staining, rusting, etc to such environments where common ferrous alloys get corroded. Stainless term is often a misnomer. The environmental condition must be mentioned prior to grade these steels as stainless for any application.

All stainless steels contain iron as the main element and chromium in amounts ranging from about 11% to 30%. Chromium provides the basic corrosion resistance to stainless steels. Only chromium containing stainless steels are known as straight chromium steels and categorized under AISI 400 series. These steels are of ferritic or martensitic microstructure and are magnetic in nature.

Nickel is added to certain grades of stainless steels, which are known as chromium-nickel stainless steel. The addition of nickel reduces the thermal conductivity and decreases the electrical conductivity. The chromium-nickel steels belong to AISI 300 series of stainless steels. They are nonmagnetic and have austenitic microstructure. These stainless steels contain small amounts of carbon because this element has tendency to make chromium carbides, which are not corrosion resistant. Carbon is undesirable particularly in the 18% chromium, 8% nickel group.

In some grade of 300 series steel, a small portion of nickel is replaced by manganese, generally in a two-to-one relationship. They are AISI/SAE 200 series of stainless steels known as chromium-nickel-manganese series. These steels also have an austenitic microstructure and they are nonmagnetic.

In these alloys, Molybdenum is also included in some stainless steel alloys. Molybdenum is added to improve the creep resistance of the steel at elevated temperatures. It will also increase resistance to pitting and corrosion in many applications.

Stainless steels can be welded using several different procedures such as shielded metal arc welding, gas tungsten arc welding, and gas metal arc welding.

The physical properties of stainless steel are different from mild steel and this makes it weld differently. These differences are:

- Lower melting temperature,
- Lower coefficient of thermal conductivity,
- Higher coefficient of thermal expansion,
- Higher electrical resistance.

The properties are not the same for all stainless steels, but they are the same for those having the same microstructure. Regarding this, stainless steels from the same metallurgical class have the similar welding characteristics and are grouped according to the metallurgical structure with respect to welding.

2.0 CLASSIFICATIONS OF STAINLESS STEELS:

2.1 Ferritic Stainless Steels – This class is so named because the microstructures of these grades of steels predominantly contain the ferrite phase. These steels are not hardenable by heat treatment and are magnetic. All of the ferritic types are considered weldable with the majority of the welding processes except for the free machining grade AISI 430F, which contains high sulphur content. The coefficient of thermal expansion is lower than the austenitic types and is about the same as mild steel. Welding processes that tend to increase carbon pickup are not recommended. This would include the oxy-fuel gas process, carbon arc process, and gas metal arc welding with CO_2 shielding gas.

The lower chromium types show tendencies toward hardening with a resulting martensitic type structure at grain boundaries of the weld area. This lowers the ductility, toughness, and corrosion resistance at the weld. For heavier sections preheat of 200°C is beneficial. To restore full corrosion resistance and improve ductility after welding, annealing at 760-820°C, followed by a water or air quench, is recommended. Large grain size will still prevail, however, and toughness may be impaired. Toughness can be improved only by cold working the weld.

If heat treating after welding is not possible and service demands impact resistance, an austenitic stainless steel filler metal should be used. Otherwise, the filler metal is selected to match the base metal.

2.2 Martensitic Stainless Steels – The martensitic stainless steels are hardenable by heat treatment and are magnetic. The low-carbon type can be welded without special precautions. The types with over 0.15% carbon tend to be air hardenable and, therefore, pre-heat and post-heat of weldments are required. A preheat temperature range of 230-300°C is recommended. Post-heating should immediately follow welding and be in the range of 650-760°C, followed by slow cooling.

If pre-heat and post-heat treatments are not possible, an austenitic stainless steel filler metal should be used. Type AISI 416Se is the free-machining composition and should not be welded. Welding processes that tend to increase carbon pickup are not recommended. Increased carbon content increases crack sensitivity in the weld area.

2.3 Austenitic Stainless Steel – Austenitic stainless steels are not hardenable by heat treatment and are nonmagnetic in the annealed condition. They may become slightly magnetic when cold worked or welded. This helps to identify this class of stainless steels. All of the austenitic stainless steels are weldable with most of the welding processes, with the exception of Type AISI 303, which contains high sulphur and Type AISI 303Se, which contains selenium to improve machinability.

The austenitic stainless steels have about 45% higher thermal coefficient of expansion, higher electrical resistance, and lower thermal conductivity than mild-carbon steels. High travel speed welding is recommended, which will reduce heat input and carbide precipitation, and minimize distortion.

The melting point of austenitic stainless steels is slightly lower than melting point of mild steels. Because of lower melting temperature and lower thermal conductivity, welding current is usually lower. The higher thermal expansion dictates that special precautions should be taken with regard to warping and distortion. Tack welds should be twice as often as normal. Any of the distortion reducing techniques such as back-step welding, skip welding, etc should be used. On thin materials it is very difficult to completely avoid buckling and distortion.

2.4 Precipitation Hardened Stainless Steel – These are high strength stainless steels, developed by a low temperature heat treatment known as precipitation hardening treatment. They precipitation hardening classes can be divided into three groups: (a) martensitic, (b) semi-austenitic and (c) austenitic. Most of these grades are better known by the trade designations of their manufacturers. Stainless W, 17-4 PH, 15-5 PH, PH 13 Mo, Custom 450, 17-7 PH, etc are to name a few. After welding of these steels, the hardening heat treatment shall be followed to restore the original properties.

2.5 Duplex Stainless Steel – Stainless steels with approximately 50-50 ferrite-austenite microstructure are commonly known as duplex stainless steels (DSS). These steels possess the beneficial effects of both ferritic and austenitic grade. The higher yield strength, better resistance to pitting & stress corrosion with an optimum cost rendered them an excellent choice for numerous specific uses. To name a few, these steels find applications in Petrochemical and refineries, Sea-water & offshore structure, Pollution control equipment, Chemical process plant, Textile industries, etc. All welding process, except oxyacetylene welding (due to carbon contamination), are used for welding of duplex stainless steels.

Combination of high strength, good corrosion resistance and a reasonable price has made duplex stainless steel an important structural material over the conventional austenitic stainless steels. A wide varieties and grades of DSS are available in the market. The major alloying elements in DSS are Cr, Ni, Mo and N. Some grads also contain W and Cu. Among the DSS category, 22Cr-5.5Ni-3Mo-0.15N is the principal duplex grade. It has a low carbon (below 0.03%) and 0.10 to 0.15% nitrogen with a 50% α and 50% γ microstructure. This grade is the most widely accepted duplex stainless steel.
The resistance to this attack is related to the composition and defined by a “pitting resistance equivalent number” (PREN) given by:

$$\mathbf{PREN = Cr + 3.3\ Mo + 16\ N}$$

The PREN should be at least 30 and in some case between 35 and 40.

3.0 WELDING OF STAINLESS STEELS:

The selection of the filler metal alloy for welding the stainless steels is based on the composition of the stainless steel. The various stainless steel filler metal alloys are normally available as covered electrodes, as bare solid wires and flux-cored electrode wires.

3.1 Shielded metal arc welding – There are three basic types of electrode coatings. These are (a) the lime type indicated by the suffix 15, (b) the rutile or titanium type designated by the suffix 16 and (c) in which rutile is partly replaced with silica by the suffix 17. The lime type electrodes are used only with direct current electrode positive (reverse polarity). The titanium-coated electrode with the suffix 16 & 17 can be used with alternating current and with direct current electrode positive. All three coatings are of the low-hydrogen type and are used in all positions. However, the type 17 is smoother, has more welder appeal, and operates better in the flat position. Next is type 16 and followed by type 15. The lime type electrodes are more crack resistant and are slightly better for out-of-position welding and for better sub-zero impact properties. The width of weaving should be limited to two-and-one-half (2.5) times the diameter of the electrode core wire. Covered electrodes for shielded metal arc welding must be stored at normal room temperatures in dry area. These electrode coatings, of low hydrogen type, are susceptible to moisture pickup. Once the electrode box has been opened, the electrodes should be kept in a dry box until used.

3.2 Gas tungsten arc welding – This process is widely used for thinner sections of stainless steel. The 2% tungsten is recommended and the electrode should be ground to a taper. Argon is normally used for gas shielding; however, argon-helium mixtures are sometimes used for automatic applications.

3.3 Gas metal arc welding & Flux cored arc welding – These processes are widely used for thicker materials since it is a faster welding process. The spray transfer mode is used for flat position welding and this requires the use of argon for shielding with 2% or 5% oxygen or special mixtures. The oxygen helps producing better wetting action on the edges of the weld. The short-circuiting transfer can also be used on thinner materials. In this case, CO_2 shielding or the 25% CO_2 plus 75% argon mixture is used. With extra low-carbon electrode wires and CO_2 shielding the amount of carbon pickup will increase slightly. This should be related to the service life of the weldment. If corrosion resistance is a major factor, the CO_2 gas or the CO_2-argon mixture should not be used.

4.0 COMMON PROBLEMS ENCOUNTERED DURING WELDING OF STAINLESS STEEL:

The problems commonly encountered during the welding of stainless steels are-

1. 475°C embrittlement

2. Hydrogen embrittlement
3. Sensitization and weld decay
4. Knife-line attack
5. Sigma phase transformation
6. Transformation to different inter-metallic phases
7. Solidification cracking
8. Liquation cracking

4.1 475°C Embrittlement – Exposure of ferritic stainless steels in the 400˚ to 565˚C temperature range or slowly cooling through this range results in a pronounced increase in hardness with a corresponding decrease in ductility. The embrittlement becomes more severe with higher chromium contents (figure-1). The reason is attributed to the precipitation of a coherent very fine chromium-rich body centered cubic phase. The effect of embrittlement can be removed by subsequent heating to 590˚C or to the normal annealing temperature of the respective grades followed by rapid cooling the steel.

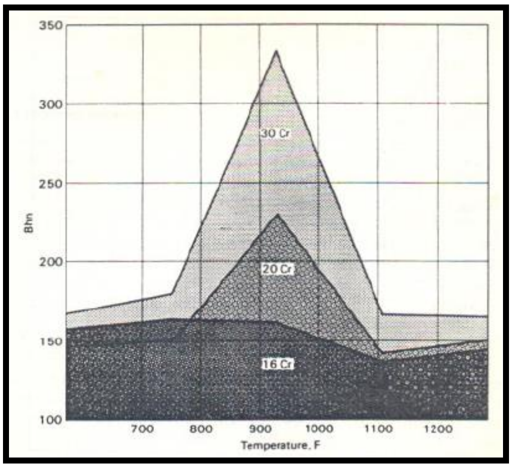
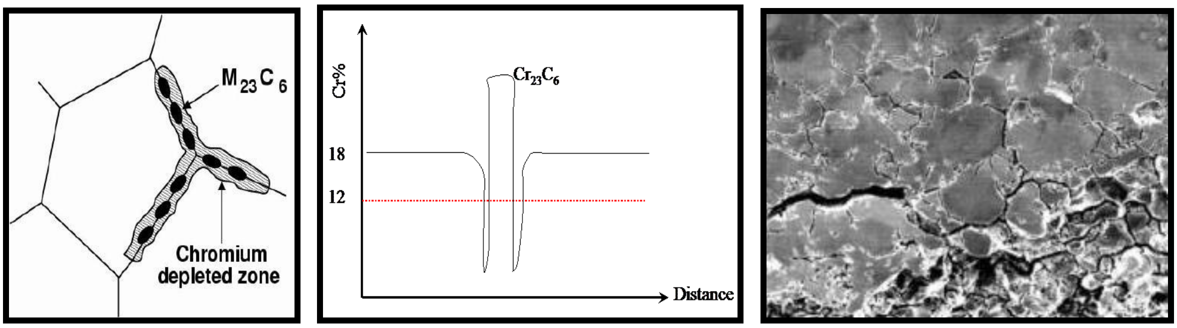


Figure-1: Effect of 475˚C (885˚F) embrittlement on hardness.

4.2 Hydrogen embrittlement – This type of embrittlement occurs during melting, heat treatment, pickling, welding, electro-chemical processing of Martensitic stainless steels. The effect reduces ductility of the steel. The embrittling effect can be removed by holding the material between 200 and 370˚C for several hours.

4.3 Sensitization & Weld decay – The phenomenon of precipitation chromium carbide in stainless steel is called sensitization. Generally occurs when the austenitic stainless steels when exposed to temperature between 425 to 815˚C. This effect is also observed in the heat affected zone during welding and thus known as 'weld decay' (figure-2). The failure occurs along the grain boundaries where the precipitation occurs (inter-granular attack), figure-2a. The area in the vicinity of carbide precipitation suffers from depletion of chromium (figure-2b) and thus looses its corrosion resistance properties (figure-2c).



(a) (b) (c)

Figure-2: Figure showing: a) chromium carbide ($Cr_{23}C_6$) precipitation along the grain boundary, b) depletion of chromium along the boundary of $Cr_{23}C_6$ precipitates c) inter-granular corrosion attack due to chromium carbide precipitation.

Sensitization can readily be avoided by following methods:

1. Use of very low carbon steels (C<0.04%) so that the amount of Chromium carbide forms is small and reduce the propensity. Figure-3 shows how the carbon accelerates the sensitization process.
2. Use of stabilizer elements those have more affinity for carbon than Chromium like; Niobium & Titanium.
3. Reheat the sensitized steel to 1050-1100˚C to dissolve the carbide precipitates and subsequent rapid cooling (water quenching) to avoid longer stay in the sensitization temperature zone.

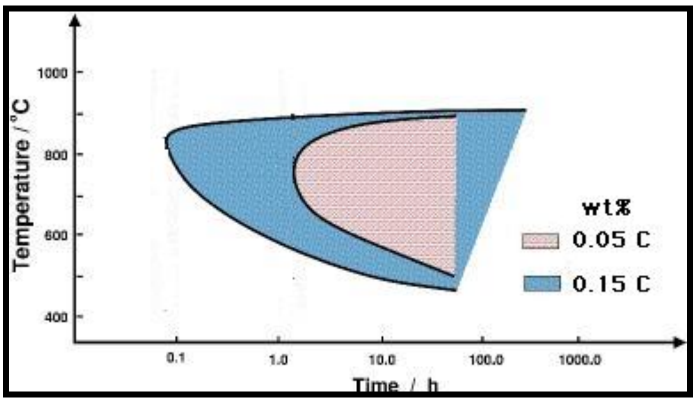


Figure-3: Schematic representation of MMAW electrical connections

4.4 Knife-line attack/corrosion – This type of failure occurs in stabilized austenitic stainless steels. While welding, the titanium or niobium carbide in the heat affected zone (HAZ) gets dissolved but on subsequent cooling chromium rich carbides ($M_{23}C_6$) are formed. This forms a depletion of chromium and causes inter-granular corrosion in the surrounding zones where niobium carbide has been dissolved. These zones are narrow and failure occurs in a straight line as if the plate has been cut by a knife. Thus, this type of corrosion is called knife-line corrosion (figure-4).

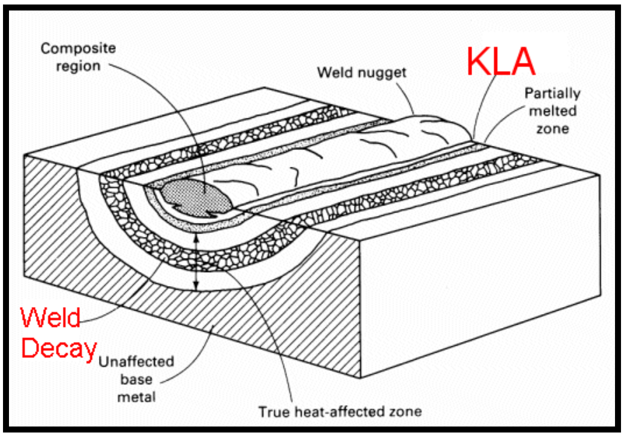


Figure-4: Schematic representation of MMAW electrical connections

4.5 Sigma phase transformation – Sigma phase is an iron-chromium (Fe-Cr) compound with tetragonal crystal structure. It contains ~29% Cr. Sigma phase precipitates when the stainless steel is held at temperature zone 590-870˚C for a prolonged time (micrograph shown in figure-5). It starts precipitation in ferrite because ferrite contains more Chromium & Molybdenum and diffusion rate of Chromium & Molybdenum is higher in ferrite than austenite. Higher percentage of delta ferrite makes the stainless steel more propensive to sigma phase transformation.

Presence of Silicon, Titanium, Niobium, Molybdenum increases and Carbon, Nitrogen, Boron, Nickel, Cobalt retards the rate of sigma phase precipitation by reducing or increasing the transformation time respectively.

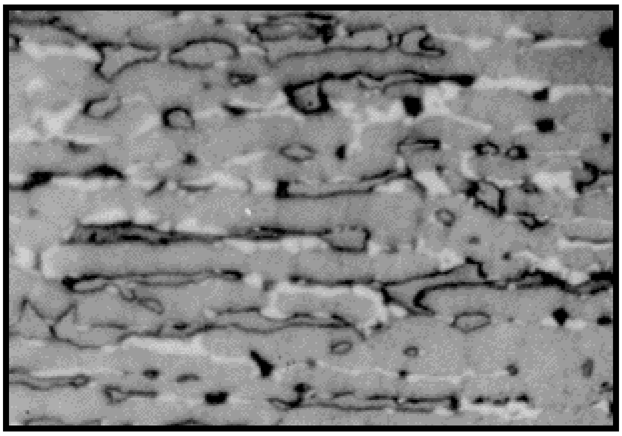


Figure-5: Sigma phase formation shown by the white patches, continuous gray is austenite and dispersed gray is ferrite.

4.6 Transformation to intermetallic phases –When the stainless steel suffers a temperature range 750-1000˚C some more precipitates form those are known as inter-metllic phases. All of them are enriched with alloying elements (Table-1) and makes the stainless steel brittle and less resistant to corrosive attack.

Once these phases have formed, the properties are restored by heating the steel to solution annealing temperature (1050-1100˚C) to re-dissolve the precipitates followed by rapid cooling (to avoid re-precipitation).

Table-1: Secondary phases in stainless steels

Phase	Fe	Cr	Mo	Ni	Mn	Si
$M_{23}C_6$	18	63	14	5	-	-
Sigma (σ)	55	29	11	5	-	-
Chi (χ)	52	21	22	5	-	-
Laves (η)	38	11	45	6	-	-
G-phase	10	2	-	55	20	13

<u>4.7 Solidification cracking</u> –This type of cracking appears along the grain boundaries during solidification. The low melting phases form a liquid film at the grain boundaries. During last solidification of those parts, shrinkage can not be compensated with further supply of liquid metals which form micro-fissures within the weld (figure-6). During further cooling these cracks may propagate to surface to appear as macro-cracks.

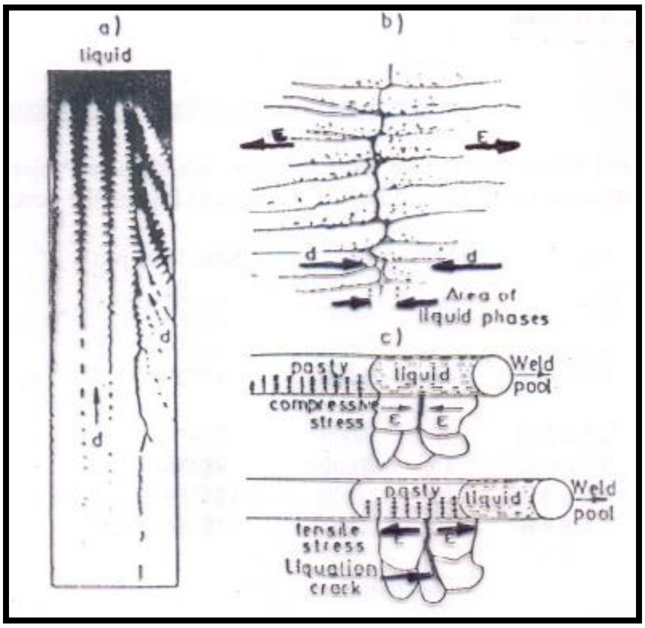


Figure-6: Schematic representation of solidification cracking – a) shows the dendrites during solidification, b) shows the segregation and c) shows the formation of cracks.

<u>4.8 Liquation cracking</u> – During welding the heat causes to melt the adjacent grain boundaries wherein there is a segregation of low melting phases. The melting point & solubility of these phases are shown in Table-2. The grain boundaries become liquid though the surrounding grains remain in the solid state. Such liquation of grain boundaries gives rise to formation of crack known as liquation crack (figure-7).

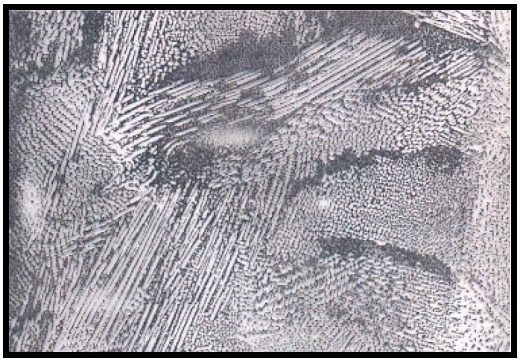


Figure-7: Photograph showing the liquation crack along the dendrites.

Table-2: Melting points and solubility of low melting phases in austenite (γ) & ferrite (α)

Constituents	Solubilities			Low melting eutectics	Melting points
	at °C	in γ	in α	Structure	°C
S	1365	0.05	0.14	Fe-FeS	988
				Ni-NiS	630
P	1250	0.2	1.6	$Fe-Fe_3P$	1048
				$Ni-Ni_3P$	875
B	1381	0.005	0.5	$Fe-Fe_2B$	1177
				$Ni-Ni_2B$	1140
				$(Fe, Cr)_2B$-Austenite	1180
Nb	1300	1.0	4.1	$Fe-Fe_2Nb$	1370
				NbC-Austenite	1315
				Nb-Ni rich phases	1160
Ti	1300	0.36	8.1	$Fe-Fe_2Ti$	1290
				TiC-Austenite	1320
Si	1300	1.15	10.5	$Fe-Fe_2Si$	1212
				$NiSi-Ni_3Si_2$	964
				NiSi	996

5.0 CARE TO BE TAKEN DURING WELDING OF STAINLESS STEELS:

The possible care & precautionary measure needs to be taken during welding of stainless steels are-

- ✓ Prior cleaning of the weld assembly.
- ✓ Selection of suitable process.
- ✓ Selection of suitable consumable (Carbon, Ferrite content).
- ✓ Joint design.
- ✓ Proper welding sequence (to avoid distortion).
- ✓ Short arc, less weaving (to avoid nitrogen pick up).
- ✓ Proper cleaning after each run (Discontinuity).
- ✓ Low heat input (Amp, Travel speed).
- ✓ Low inter-pass temperature.
- ✓ Stress relief & Quench annealing.